A preliminary clinic dosimetry study for synchrotron radiation therapy at SSRF

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Abstract Synchrotron radiation (SR) represents a unique and innovative anti-cancer treatment due to its unique physical features, including high flux density, and tunable and collimated radiation generation. The aim of this work is to assess the dosimetric properties of SR in Shanghai Synchrotron Radiation Facility (SSRF) for potential applications to clinical radiation oncology. The experiments were performed with 34 and 50 keV X-rays on the BL13W biomedical beamline of SSRF and the 6 MV X-rays from ARTISTE linac for the dosimetry study. The percentage depth dose (PDD) and the surface dose of the SR X-rays and the 6 MV photon beams were performed in solid water phantom with Gafchromic EBT3 films. All curves are normalized to the maximum calculated dose. The depth of full dose buildup is about 10 µm deeper for the monoenergetic X-ray beams of 34 and 50 keV. The beam transmits through the phantom, with a linear attenuation coefficient. The profile in the horizontal plane shows that the dose distribution is uniform within the facula, while the vertical profile shows a Gaussian distribution of the dose. The penumbra is less than 0.2 mm in the horizontal profile. Gafchromic EBT film may be a useful and convenient tool for dose measurement and quality control for the high space and density resolution. It is therefore important to gain a thorough understanding about the physical features of SR before this novel technology can be applied to clinical practice.

Key words Radiation therapy, Synchrotron radiation, Physical features, Dosimetry

1 Introduction

Radiation therapy, along with surgery and chemotherapy, is the primary option for cancer treatment. Radiotherapy has been used to treat 60%–70% of cancer patients. The goal of radiation therapy is to deliver the maximum dose to a tumor and render the minimum radiation damage to surrounding normal tissues. The existing techniques of radiotherapy, including conventional MV X-ray radiation therapy, have some limitations in terms of physical and radiobiological aspects. Therefore, it is imperative to develop new technologies to maximize the dose to a tumor and minimize radiation damage to surrounding normal tissues. Recent advances in synchrotron radiation (SR) have offered a new option to radiotherapy. The Shanghai Synchrotron Radiation Facility (SSRF), a third-generation synchrotron radiation light source available for the users since 2009, provides an invaluable tool for cancer treatment. Two SR-based techniques (SRT) have been reported [1,2]: Stereotactic synchrotron radiotherapy (SSRT) and microbeam radiation therapy (MRT). The first patient was admitted for SSRT in late June 2012 at European Synchrotron Radiation Facility (ESRF), while MRT has been in pre-clinical radiosurgery dedicated to treating brain tumors initially[3]. As the biomedical beamline of SSRF is similar to the ESRF beamlines for developments in SSRT and MRT, in terms of beam intensity and stability, it shall be possible to deliver enough dose to a tumor target within a short period of time, for potential treatments of aggressive tumors with hypofractionated irradiations like SSRT in ESRF. Therefore, it is necessary to gain a thorough understanding about the parameters related to radiation therapy on the SSRF beamline, including the skin dose, dose rate and X-ray spectrum, before it can be applied to clinical practice. The purpose of the present study

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was to investigate the physical features of SSRF-based synchrotron radiotherapy.

2 Materials and methods

2.1 General data

The experiments were performed on the BL13W biomedical beamline of SSRF, which runs beam bunches of 3.5 GeV electrons circulating a 432-m circumference, and 34 and 50 keV X-rays were selected from the synchrotron radiations generated from a wiggler. Photon beams from a 6 MV ARTISTE linac (Siemens Corp.) were used, too, for the dosimetry study. Dosimetric verifications of the SR X-rays and the 6-MV photon beams were performed at different depths in the solid water (PTW Solid Water Phantom).

2.2 Film dosimetry

Medical radiation dosimetry can be performed with radiochromic films capable of producing a permanent visible color change upon irradiation. In this work, Gafchromic EBT3 radiochromic film (International Specialty Products, NJ, USA) was used for radiation-induced auto-developing X-ray analysis. The film has high spatial resolution (5 μm), high sensitivity and good uniformity of response (<1.5%). Also, it can be used for wide dose range (0.01 Gy to 40 Gy) measurements with X-rays in wide range energies (from keV to MeV). All irradiated films were scanned by an EPSON 10000XL scanner (EPSON, JAPAN), and analyzed by FilmQA-PRO software (International Specialty Products, NJ, USA).

A calibration curve was established using the 6 MV X-rays. In the calibration, a 13-mm thick PMMA plate was used to cover the films backed by a 5-cm thick tough-water phantom material.

3 Results and discussion

For feasibility study of clinical SSRT trials on the BL13W beamline at SSRT, it is essential to know its specific features, i.e. the dosimetric characteristics of linearity, reproducibility, uniformity, penumbra, surface dose and percent depth dose (PDD), which were investigated experimentally with the radiochromic film. It was found that the film is a useful and convenient tool for dose measurement and the quality control of SR X-rays.

3.1 PDD of SSRF

In radiotherapy, PDD is the key parameter for calculating the prescribed dose and the tissue or tumor absorption dose. A PDD curve relates the absorbed dose with medium depth along the axis of the beam. The doses are expressed in percentages of the maximum dose, referred to as D_{max}. The doses are measured generally in water or "water equivalent" plastic in an ionization chamber, as water is similar to human tissue in radiation scattering and absorption.

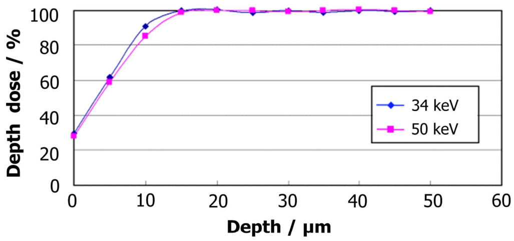

Fig. 1 Central axis depth dose in surface of the solid water phantom.

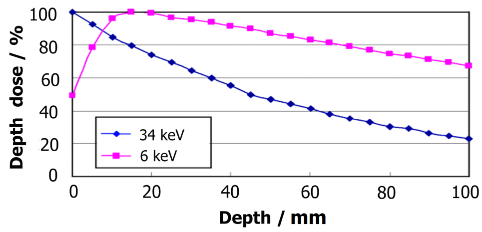

Fig.2 Absolute transmission of 34 keV SR X-rays and conventional 6 MV X-rays in the solid water phantom.

Low energy X-rays have a high surface dose with a shallow build-up depth. Fig.1 shows the central axis depth dose, normalized to the maximum dose calculated, in surface of the solid water phantom, obtained from X-ray film measurements with 34 keV or 50 keV X-rays on the BL13W beamline. The depth of full dose buildup is about 10 μm deeper for the monoenergetic X-ray beams of 34 and 50 keV. The results are similar to those obtained at ESRF[4]. The beam transmits through the phantom, with a linear attenuation coefficient[5]. This is consistent with the predicted results by simulations[6].

In Fig.2, the PDD of 34 keV X-rays is compared with X-rays from the 6 MV linac. The dose

attenuation with 34 keV X-rays in the phantom is much quicker than that with the 6 MV X-rays.

3.2 Facula features

Synchrotron radiation has better reproducibility and uniformity. We irradiated two films in different hours with 34 keV X-ray of the same parameters, and the difference in the absorbed dose was less than 4%. Fig.3 shows the facula size. It is about 4 cm in length and 4 mm in height. The profile in the horizontal plane (Fig.4) shows that the dose distribution is uniform within the facula, while the vertical profile (Fig.5) shows a Gaussian distribution of the dose.

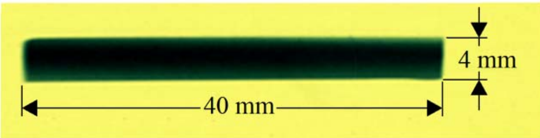

Fig.3 Very small facula of the 34 keV SR X-ray.

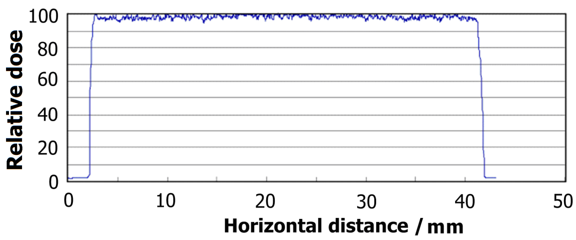

Fig.4 A profile in the horizontal plane, showing good uniformity of the 34 keV SR X-ray.

The facula center is of the brightest, indicating non-uniformity of the dose in the radiation field, hence the necessity of intensity modulated radiation therapy technique in the vertical plane.

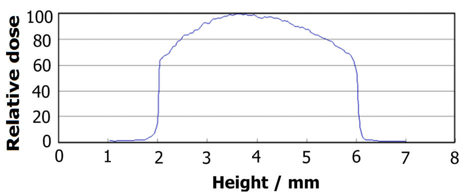

Fig.5 A profile in the vertical plane, showing a maximum facula width of only 4 mm for the 34 keV X-ray.

In X-ray therapy, metal or plastic blocks are used to improve the dose distribution. As shown in Figs.4 and 5, the dose curves are very sharp at the facula edges. The penumbra is less than 0.2 mm in the horizontal profile (Fig.4). Penumbra has a major impact on uniformity of isodose distributions in radiation therapy. For the 34 and 50 keV SR X-rays, the penumbra is so small that organ at risk (OAR) surrounding the tumor can be protected. Synchrotron X-rays are of extraordinarily high flux density and small divergence, with sharply defined beam edges at depths in the body. Compared with conventional radiotherapy, SR-based radiotherapy is able to deliver a higher fraction dose to the target within a shorter time.

In conventional radiation therapy, tumor movements during irradiation consequently result in missing of the treated tumor. Because of the high flux density of synchrotron X-rays, the tolerance of tumor motion can be well within the limits of accuracy in SR-based radiotherapy, which ensures higher therapeutic effects than conventional irradiation.

3.3 Field expansion

The X-ray beam available at the BL13W beamline has a maximum height of 4 mm, but the size of a tumor is usually larger than facula. A scanning method can expand the irradiation field. A tumor volume can be outlined according to CT images. Plumbum masks are made in the beam view to define the incoming beam to the tumor shape. Fig.6 shows an expanded irradiation field. Fig.7 is the profile. If two consecutive faculas are interlaced, the dose is overlapped and the high dose may cause injury to normal tissues. If the consecutive faculas are separated, the dose is not enough, and low dose may increase the risk of tumor recurrence. How to adjoin the facula is an important problem for SR-based radiation therapy at SSRF.

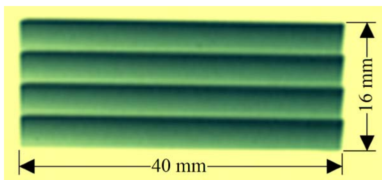

Fig.6 Field expansion.

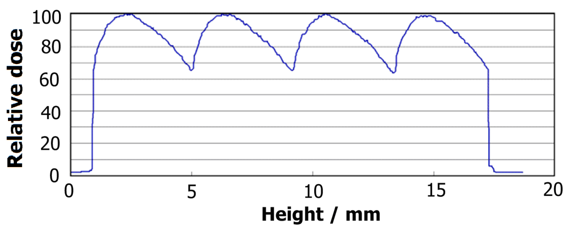

Fig.7 A profile in the vertical plane for the expanded irradiation field.

3.4 Dose calculation and treatment planning

A treatment planning system for ESRF ID17 clinical trials is on the way by collaboration with the CHU-INSERM team and the company DOSIsoft[7] for SSRT application only. A realistic simulation of this distribution is necessary for treatment planning and evaluating the experimental results.

In SRT, tumors are irradiated with very high doses. High flux synchrotron X-rays allow for extremely rapid irradiation, devoid of collimation due to micro-movement fluctuations of the target. The absolute dose to the target needs to be calculated and delivered accurately. Monte Carlo based calculations have been carried out for SRT to calculate the dose distribution that is finally needed for treatment planning[8–10]. These data allow a description of the physical dose deposition, but the reliable prediction of the biological effect has not been achieved. Especially in terms of the size of the treatment volume, the knowledge is limited to small volumes in the brain. Accordingly, a real optimization of the treatment parameters is not yet feasible. To set up a treatment-planning program for human patients, additional data for normal tissues and tumors are necessary[7].

3.5 Dose profile evaluation

For SRT, dosimetry tests should be done before and/or after patient treatment with respect to dosimetric films, TLDs or gel dosimetry for patient safety. Dosimetry of SRT beams should record the total absorbed dose to the tissue. The calculation result should be compared with the dosimetric and microdosimetric measurements using ionization chambers, MOSFET detectors, TLD or radiochromic films[11–15], knowing that the measurement readout ensures the irradiation quality.

To get better agreement with the experimental data and predict a better dose in therapeutic application, it is necessary to further refine the MC simulation of SRT[4]. In addition, systematic analysis of the therapeutic gain for different microdosimetric patterns on the basis of the beam energy, beam shape and overall field size is still evolving for SRT of targets in experimental animals.

3.6 Quality assurance for SSRF

In radiotherapy, quality assurance (QA) plays an important role in the workflow. SRT is a technique designed to deliver radiation therapy very precisely to tumors. The technology used in SRT allows external beam radiation to be delivered with pinpoint accuracy. However, delivery of treatment in an accurate and consistent manner is by no means easy to achieve, since the radiation therapy process is a complex interweaving of a number of related tasks for designing and delivering radiation treatment. QA of the radiation therapy equipment is primarily an ongoing evaluation of functional performance characteristics. Accurate radiotherapy determines the therapeutic effect, and high accuracy is an obligation for prescribing a precise dose. QA is a prerequisite for the treatment setting. QA in radiotherapy ensures consistency of the medical prescription, and safe fulfillment of the radiotherapy related prescription. For patient treatment, the accuracy of the location and dose should be checked frequently. Although the synchrotron accelerator has very high accuracy and precision, the mechanical isocenter should be checked aperiodicly. The center of the facula may shift after several years.

4 Conclusion

Synchrotron radiation has many physical and biological advantages for radiation therapy, and related medical research plays an important role in radiation therapy. SR therapy represents a great potential radiation source to be applied in the treatment of cancer. The results of our trial show that the physical features of SSRF are similar to those of the light source abroad. We believe that SSRF will be applied in radiation oncology in the near future. However, the transition from animal experiments to clinical therapy in human patients appears to be more complex. Further dosimetric studies are necessary to better predict the dose in clinical applications. A dose measurement within a different tissue density phantom with other methods is required. The film can measure the continuous dose distribution in the plane with the high space and density resolution, which may be a useful and convenient tool for dose measurement and

quality control. With such knowledge, it can be anticipated that advancements in the conventional tools will lead to the betterment of medical practice[16].

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